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Control Electronics for Atomic Force Microscopy

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We describe the control electronics for our Atomic Force Microscope (AFM). The set of electronic devices described here allow convenient operation of an Atomic Force Microscope. The key device is the Force Controller, which automates the otherwise tedious and time consuming readjustment of the force to a preset value by controlling two gated feedback loops. The preset value of the force can be easily changed by simply turning a potentiometer. This automated system allows us to obtaion reliable data, with known force4s, despite piezoelectric creep and thermal drift in the force determining mechanical setup. The electronic devices and concepts presented here work for AFM's that use tunneling, capacitance measurements or optical interferene to sense small deflections of the spring. as (150 nm)^2 can be easily prepared in air by melting a gold wire with an oxyacetylene torch. Features with characteristic dimensions as low as 10 nm can be written and observed on these terraces with a Scanning Tunneling Microscope (STM). The features are appreciably

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ABSTRACT: We describe the control electronics for our Atomic Force Microscope (AFM). The set of electronic devices described here allow convenient operation of an Atomic Force Microscope. The key device is the Force Controller, which automates the otherwise tedious and time consuming readjustment of the force to a preset value by controlling two gated feedback loops. The preset value of the force can be easily changed by simply turning a potentiometer. This automated system allows us to obtain reliable data, with known forces, despite piezoelectric creep and thermal drift in the force determining mechanical setup. The electronic devices and concepts presented here work for AFM's that use tunneling, capacitance measurements or optical interference to sense small deflections of the spring.

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The AFM in our laboratory uses a piezo tube[9] with a diameter and a length of 6.4 mm each. The driving voltages of ±150 V give a range of 340 nm for the x and y scan axis. The range of the z axis is 300 nm, using the same voltage range. We have not measured the nonlinearities and hysteresis of the x and y scanning at the full range and only use the full range for finding surface features. On the 20 nm range used for imaging the scanning is linear to within a few percent. A slab of piezo material forms the z' piezo, which has a range of 90 nm with a driving voltage of ±150 V. The range of forces in our AFM depends on the force constant of the spring and the possible range of deflections: from 45 nm down to < 1 nm. The force of a spring with a force constant of 100 N/m therefore can be adjusted between $< 10^{-7}$ N and 4.5×10^{-6} N, one of 1 N/m between $< 10^{-9}$ N and 4.5×10^{-8} N.

Several methods have been proposed for continuously keeping the force from changing while the AFM's dimensions are changing due to thermal expansion and contraction or piezo creep. Pethica[10,11] proposed modulating the force applied to the surface to detect the absolute force. McClelland *et al.*[3] proposed modulating the attachment of the spring for the same purpose. The electronics described here does not include modulation techniques, yet keeps the force within the desired limits by automatic periodic readjustment of the force sensor.

This paper discusses the operating principle and electronics layout of our AFM. It includes descriptions of the key devices found in the system: the two Error Amplifiers, and the Force Controller, all built in our laboratory. In addition, a scanning and image acquisition system[12] is necessary.

II. OPERATING PRINCIPLES

Our AFM is controlled by two feedback loops: the main feedback loop which controls from the spring by a distance d, at which the preset tunneling current is flowing. The spring itself is deflected by the sample by Δx from its undisturbed position. On a trigger signal (either manual or after a fixed number of images) the Force Controller: 1) stops the scanning, 2) retracts the sample from the tip (the spring will return to its undeflected position $d + \Delta x + a\Delta t$from the sensing electrode, where Δt is the time since the last readjustment and $a\Delta t$ is the distance drift has moved the spring relative to the sensing electrode), 3) places the main feedback loop on hold, and 4) turns on the auxiliary feedback loop and moves the sensing electrode over the distance $\Delta x + a\Delta t$ such that the separation between spring and sensing electrode is again d, at which the preset tunneling current will flow. 5) The Force Controller then waits until the tunneling current between the spring and the sensing electrode has settled to its preset value (the new zero-deflection position of the spring is now determined!), 6) puts the auxiliary feedback loop back on hold, 7) increases the distance between the spring and the sensing electrode a set amount to $d+\Delta x$, 8) turns on the main feedback loop and advances the sample towards the tip and spring until the spring is deflected by Δx by the sample. The separation between the spring and the sensing electrode is again d, at which the preset value of the tunneling current between the spring and the sensing electrode flows, and finally 9) restarts the scanning.

We present here block schematics showing the functioning of our electronics. The detailed schematics are much too voluminous to be included in this brief report. Upon request, however, we will gladly send the complete schematics the interested readers.

III. ELECTRONICS LAYOUT

Fig. 2 shows the block schematics of our AFM electronics. The AFM is sketched in the upper left. It consists of a sample mounted on the z-piezo. The outer electrode of the z-piezo is divided into 4 segments driven by x, y, -x and -y voltages (counter clockwise), electrodes of the z piezo to move the sample past the stationary tip. The scan start/stop output of the Force Controller is connected to the start/stop input of the digital scanner to inhibit scanning during the force sensor readjustment.

The image Storage Device[12] is used for digitizing, storing and displaying grey scale images and converting them to video signals for storage on an video recorder (VCR). The z signal is preprocessed in a signal conditioner, which adjusts the z range to get the maximum possible resolution out of the limited digitization range of our image storage device. The stored data can be transferred[13] to a personal computer[14] for further processing.

IV. ERROR AMPLIFIERS

Fig. 3 shows block schematics of the Error Amplifiers[15]. In the Error Amplifier for the main feedback loop (see Fig. 3*a*), the input voltage, which is the converted tunneling current between the sensing electrode and the spring, is added to a reference voltage that determines the preset amount of tunneling current. The resulting error in the tunneling current is integrated by an analog integrator. The Error Amplifier can be adjusted for an upper frequency limit (unity gain) between 1 Hz and 100 kHz[16]. The input of the integrator can be grounded through an analog switch so that the the output voltage is held. An additional offset voltage is added to the output of the integrator. The sum is amplified by 15 to cover a ±150V range (the maximum power supply voltage for the high voltage operational amplifiers used[17]).

The Error Amplifier for the auxiliary feedback loop (see Fig. 3*b*) differs from the Error Amplifier for the main feedback loop by its digital integrator. The absolute value of the current error controls the count frequency for the 12 bit up/down counter. A comparator sets the count direction depending on the polarity of the error in the tunneling current. The 12 bit output of the counter is used as the input to a 12 bit digital to analog converter.

After another delay, the Error Amplifier in the auxiliary feedback loop is turned on and the offset voltage on the z' piezo is returning to zero with exponentially decreasing speed, thus advancing the sensing electrode to the spring. If there were no thermal drifts or piezo creep, the tunneling current would be at its preset value. These two actions are carried out simultaneously to prevent the sensing electrode from smashing into the spring in case the spring drifted toward the sensing electrode. The sequential logic of the Force Controller then waits until the tunneling current has stabilized at its preset value. This indicates that the new zero deflection position of the spring has been found. After the tunneling current has settled, the Error Amplifier in the auxiliary feedback loop is deactivated and holds the output voltage. After a delay which prevents interference with the holding of the output voltage, the offset voltage for the auxiliary feedback loop is turned on again, moving the sensing electrode away by Δx from the spring. After another delay the Error Amplifier for the main feedback loop is turned on again and begins controlling the sample position. At the same time the offset voltage for the main feedback loop is reduced exponentially to zero. This causes the sample to move toward the tip and to deflect the spring until the preset tunneling current flows again between the sensing electrode and the spring. The Force Controller then waits until the offset voltage is zero and restarts scanning. Turning on an offset voltage (for either feedback loop) is quick so that separation of either the sample from the tip or the sensing electrode from the spring is achieved even under adverse conditions. When either offset voltage is turned off, it approaches zero exponentially so that the approach of either the sample to the tip or the sensing electrode to the spring happens smoothly.

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12. We use a combination of an image storage device (Arlunya TF5000 Image Processor, Princeton Electronic Products, North Brunswick, N.J.), a digital xy-scanner (RS1200 X,Y Raster Scanner, Physicon Corporation, Boston) and a homebuilt interface box.

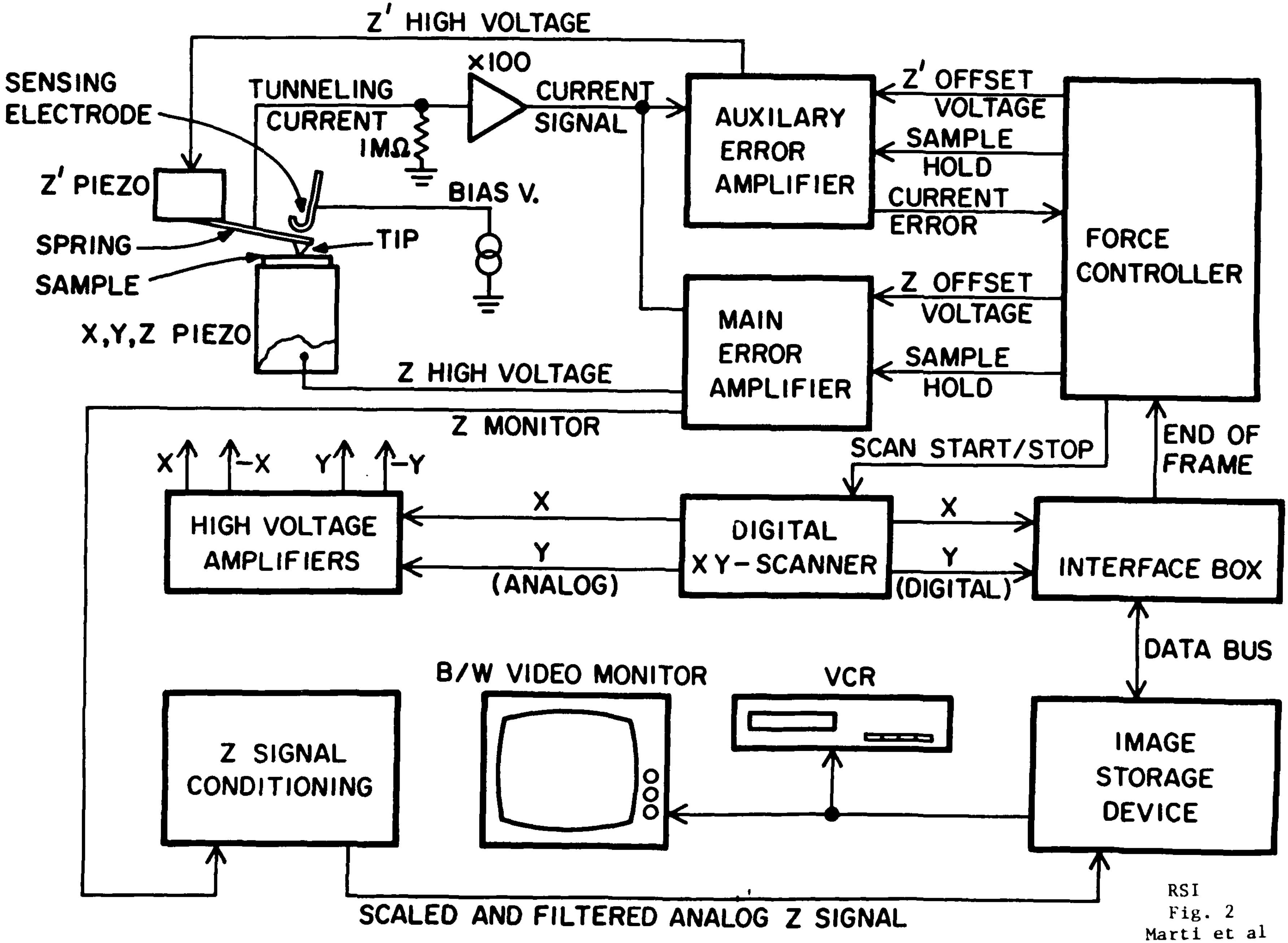
FIGURE CAPTIONS

Fig. 1. The Atomic Force Microscope probes surfaces by measuring the force between a spring mounted tip and a sample. The sample is mounted on a x,y,z piezo. $\pm$x and $\pm$y scan voltages move the sample in a raster scan fashion past the stationary tip. A feedback loop measures the tunneling current between the spring and the sensing electrode and adjusts the z position of the sample to keep the deflection of the spring constant.

Fig. 2. Block schematics of our AFM electronics. The tunneling current between the spring and the sensing electrode is fed into two Error Amplifiers. The Error Amplifier in the main feedback loop moves the sample by applying voltages to the z piezo. The Error Amplifier in the auxiliary feedback loop changes the separation of the spring and the sensing electrode by applying voltages to the z' piezo. Both Error Amplifiers are controlled by the Force controller. Scanning is done by a digital xy-scanner that drives +x, -x, +y, and -y electrodes that are also on the z piezo.

Fig. 3 a) Main Error Amplifier and b) auxiliary Error Amplifier. See the text for details.

Fig. 4. Force Controller. This unit controls the Error Amplifiers of Fig. 3. See the text for details.



RSI
Fig. 2
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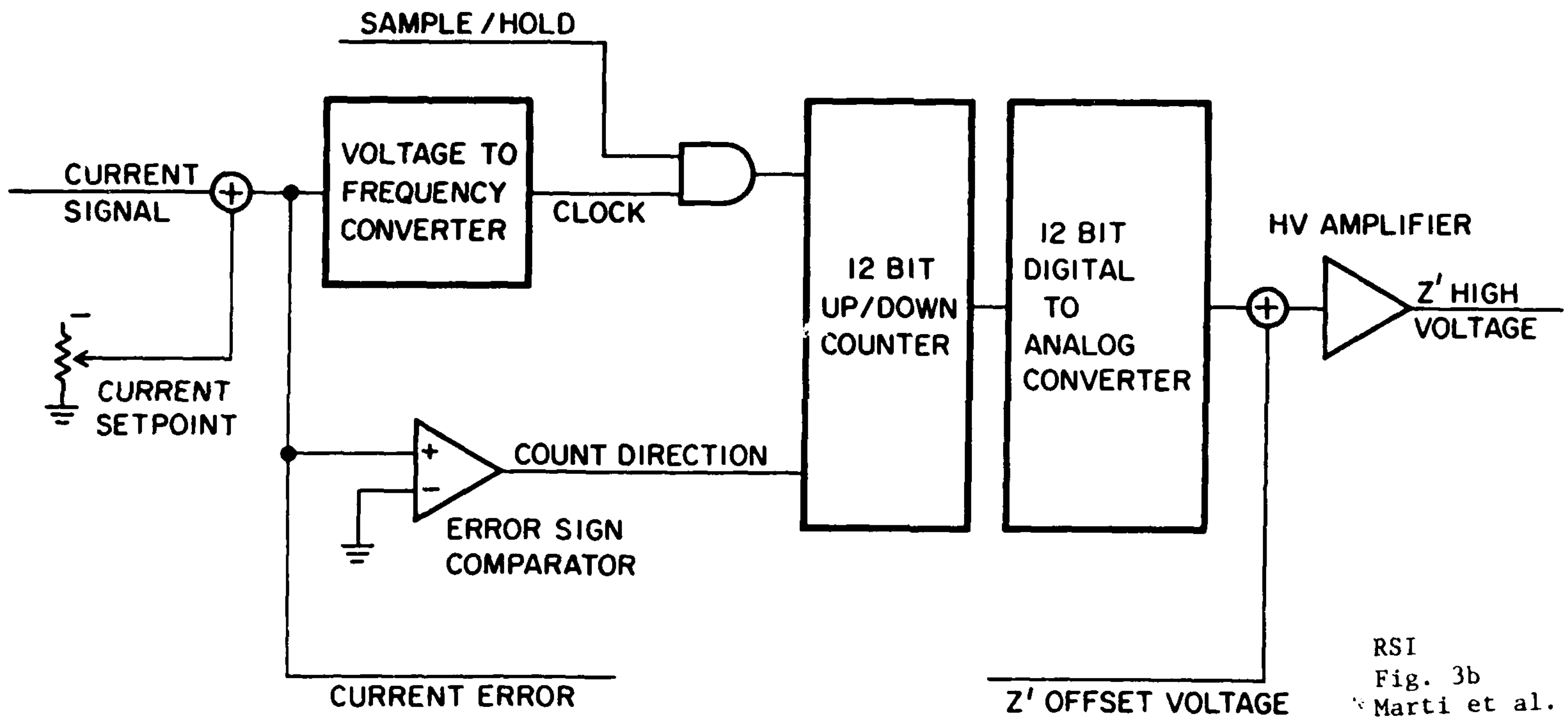

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